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Final Report

Wireless Local Area Network for ITS Communications Using the 220 MHz ITS Spectral Allocation

J. V. Krogmeier
N. B. Shroff

April 2000

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Wireless Local Area Network for ITS Communications Using the 220 MHz ITS Spectral Allocation

By

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16. Abstract

The objective of this project was to design a radio architecture using the ITS spectral allocations in the 220-222 MHz Land Mobile band which provides a multi-mode operation optimized for point-to-point, mobile, and multiple access communications. A radio performance goal was to achieve greater than 3 bits/second/Hz transmission efficiency for mobile applications, and greater than a 5 bits/second/Hz transmission efficiency for point-to-point applications. An additional important goal of this project was to explore potential ITS applications of the modem technology particularly as applied to an application in sensor telemetry concentration. The fixed point modem will be deployed for remote surveillance camera control as a part of the Borman Expressway Advanced Traffic Management System in northern Indiana. In addition, a version of this communications architecture is being consider as a product for ITS applications by Welkin Systems of San Diego, CA.

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Table of Contents

ABSTRACT 3

INTRODUCTION 3

2. PROBLEM STATEMENT 5

3. OBJECTIVES OR PURPOSE 6

4. WORK PLAN 6

5. ANALYSIS OF DATA 7

5.1 Further Results on Transmitter Diversity 7
5.1.1 Transmitter Diversity and PSAM 7
5.1.2 High Rate QAM Codes 9

5.2 TESTING 11

5.2.1 Field Testing of the Point-to-Point Modem 11
5.2.2 Field Testing of the Mobile Modem 12

5.3 MULTIPLE ACCESS AND NETWORKING RESULTS 15

6. CONCLUSIONS 16

7. RECOMMENDATIONS 16

8. IMPLEMENTATION SUGGESTIONS 16

REFERENCES 19

LIST OF TABLES 20

LIST OF FIGURES 20

Abstract

The objective of this project was to design a radio architecture using the ITS spectral allocations in the 220-222 MHz Land Mobile band which provides a multi-mode operation optimized for point-to-point, mobile, and multiple access communications. A radio performance goal was to achieve greater than 3 bits/second/Hz transmission efficiency for mobile applications, and greater than a 5 bits/second/Hz transmission efficiency for point-to-point applications. An additional important goal of this project was to explore potential ITS applications of the modem technology particularly as applied to an application in sensor telemetry concentration. A related JTRP project has fabricated a prototype of the fixed point modem for deployment in remote surveillance camera control as part of the Borman Expressway Advanced Traffic Management System in northern Indiana. In addition, a version of this communications architecture is under development by Welkin Systems in San Diego, CA.

Introduction

The research performed in this project is intended to complement the communications architecture implemented in the Phase I Borman Expressway Advanced Traffic Management System (ATMS). A similar communications architecture is under development for the Phase II system as well. One of INDOT's major concerns in the design of the Borman ATMS was scheduling the project during a period of frequent construction along the expressway. Experience has shown that communications systems using buried cable or fiber can experience frequent and prolonged outages during construction phases. For this reason wireless communications was chosen as the backbone of the system. Some of the factors that came into play during the communications architecture selection were the need for a large bandwidth for video transmission over a wide geographical area, a requirement for fast deployment, and a need for low operating cost. To best meet the design constraints, a communications architecture based upon spread spectrum radio technology was chosen. A block diagram of the primary links in the Phase I system is shown in Figure 1. The system is used to transmit sensor telemetry and compressed video taken from cameras at the three interchanges to the traffic management center (TMC) and to the incident response vehicle (IRV).

As shown in the figure, the backbone link is constructed with a spread spectrum radio at center frequency 5.7 GHz (C band) and 125 MHz bandwidth. The link provides point-to-point communications at 1.544 Mbps between the TMC located near interstate route 65 and a relay station located at INDOT's Gary subdistrict. The three sensor-instrumented interchanges for Phase I (Kennedy Avenue, Cline Avenue, and Burr Street) are joined individually to the relay station via 384 Kbps links. These links operate at 2.45 GHz (S band) using approximately 40 MHz of bandwidth. In addition, there are mobile spread spectrum links between the IRV and the three interchanges also operating in the S band at

384 Kbps. A global positioning system (GPS) receiver in the IRV is used to determine the closest of the three interchanges in order to select the best channel for transmission. All of the links use time-division multiplexing to achieve full duplex operation.

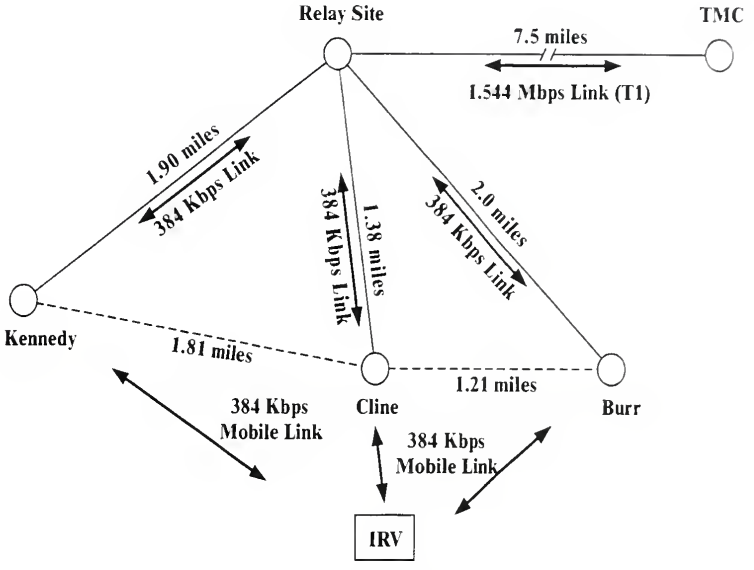


Figure 1: Basic Communications Architecture of the Phase I Borman Expressway ATMS.

Figure 1 shows the high capacity backbone communications architecture for the Phase I Borman. In Figure 2 is shown more detail on the interface between this backbone and the traffic surveillance sensors, the IRV, and the video surveillance cameras. Shown shaded in the figure are the wired connections to the traffic surveillance sensors located in the vicinity of each of the three intersections. An ATMS, like that on the Borman Expressway, relies upon a geographically distributed set of sensors which report information on traffic counts, velocity, and vehicle classification (i.e., car or truck). The sensors have a range of capabilities; on the Borman there are inductive loops, microwave radars, video cameras, ultrasonic presence detectors, and laser range profilers. The sensors are often grouped into clusters centered around an interchange where a roadside cabinet contains a local processor which does some preliminary data analysis and reduction. The traffic sensors in a cluster must be able to send their data to the roadside cabinet processor and they must be able to receive control information from it. The majority of traffic surveillance sensors require only a very small data rate capability as they operate asynchronously and produce output only when a vehicle enters the field of

view[1]. A few of the common traffic sensors, e.g., video cameras and range profilers, can require high data rates depending upon their operating mode.

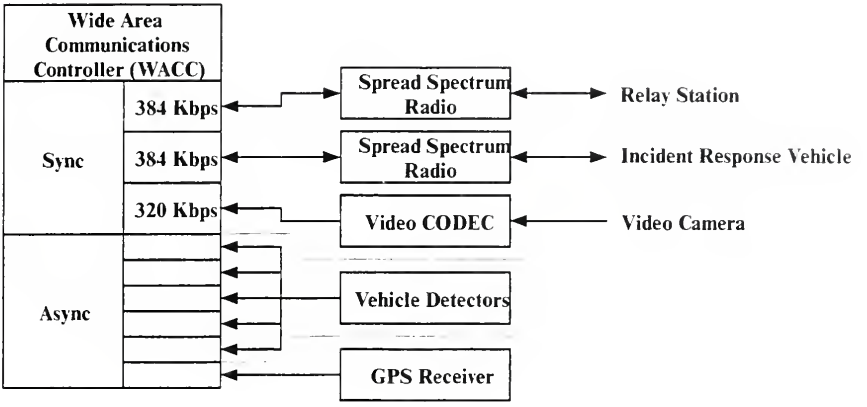


Figure 2: Wide Area Communications Controller and Various Interfaces

2. Problem Statement

The problem in this project is to do research leading to the development of a communications architecture for wireless connection of traffic surveillance sensors and certain IRV communications functions to the WACC. The proposed communication system design is to be aimed at applications needing relatively low data rates. The research is targeted toward the use of the narrowband channels in the ITS spectral allocation at 220 MHz. These channels were allocated to the Federal Highway Administration in 1992 for use in ITS applications having national implications and benefits, including selected research experiments and operational tests. In order to make such a scheme practical, the 220 MHz communications architecture will be required to support high bandwidth efficiency[2] and operation optimized for multiple access in an outdoor local area network configuration. The objectives and the individual tasks given later in this proposal are all related to this goal.

[1] As an example, the Doppler radar used on the Borman outputs a message of length 32 bits with every vehicle detection. At the average Borman traffic volume this amounts to a data rate of only 16 bits per second.

[2] We define the spectral (or bandwidth) efficiency of a communication link at the physical layer to be the data rate available to higher level functions divided by the bandwidth of the link.

3. Objectives or Purpose

The research program described in this report was designed to address three technical challenges which must be met in order to prove the feasibility of the proposed 220 MHz communications architecture. The three technical challenges are:

- the design of effective methods for using diversity in transmission,
- the design of efficient methods for physical layer synchronization in burst transmission, and
- the design of an efficient network architecture for multiple access operation.

An additional goal of this work was to further investigate the applications for this technology in ITS problems. As a first application of the technology developed in this proposal we envision a local area network for traffic sensor control and telemetry transmission. The result of a successful research program will be a practical communications architecture for bandwidth efficient use of narrowband RF channels. While the resulting technology will not be limited by the application, an ideal opportunity exists to provide for efficient use of the ITS 220 MHz channels. ITS itself promises many benefits to the nation in its potential to enhance the efficiency of existing road networks, thereby reducing road congestion, and improving travel safety and air quality. Data communications are an essential part of FHWA plans for ITS deployment and bandwidth efficient and flexible data communications products are important for obvious economic reasons.

4. Work Plan

The usable bandwidth per channel in the ITS spectrum allocation is approximately the same as that in a wireline telephone modem. However, spectral efficiencies of telephone modems approach 9 bps/Hz while the spectral efficiencies of cellular phone modems are only around 1 bps/Hz. The difference is due to the severity of channel impairments in the wireless case. Approaching wireline efficiency in a wireless modem requires a significant step in design sophistication.

The amelioration of the effects of multipath propagation is the single most important consideration in the design of a wireless communication system. In the general case, multipath propagation causes both intersymbol interference (ISI) and time-varying fading. However, in a narrowband system the symbol time is very long compared to the multipath delay spread on the channel. For example, when using the ITS spectral allocations, the symbol time is lower bounded by 250 ms while the multipath spread is rarely greater than 2 microseconds. In effect, the multipath is combined into a single multiplicative distortion process (i.e., frequency nonselective fading). While this environment generates very little ISI and rarely requires sophisticated equalization techniques, the multipath distortion process can produce significant signal fading on mobile links and significant performance variation with antenna location on stationary links.

This research program of this proposal is designed to address three specific technical challenges which must be met in order to prove the feasibility of the proposed communications architecture. The three technical questions are:

- What is the best solution to utilize diversity techniques to ensure robustness to network node placement and changes in electromagnetic scattering environment after initial deployment?
- What is the best design for burst mode synchronization given the necessity for low overhead in order that high spectral efficiency be maintained?
- What are the best choices for network layer protocols given the need for low overhead and taking account of the nature of traffic data in ITS applications?

5. Analysis of Data

5.1 Further Results on Transmitter Diversity

The main objective in our effort at physical link optimization is to design, implement, and field test coding schemes capable of achieving bandwidth efficiencies of 3 bps/Hz and higher. This is an area of intense activity in the communications literature wherein schemes have been proposed based upon multilevel block and trellis codes [1], parallel concatenated convolutional codes [2], and I-Q trellis codes [3]. As described in the following two sections, we have investigated a number of these methods with the idea of clarifying the performance/complexity tradeoffs in the context of our experimental 220 MHz system. The work described here also involves an investigation of optimal receiver diversity techniques for pilot symbol assisted (PSAM) modulations.

5.1.1 Transmitter Diversity and PSAM

The reduction of the detrimental effects of multipath propagation is an essential consideration in the design of a wireless communication system. In the general case, multipath propagation causes both intersymbol interference (ISI) and time-varying fading. However, in a narrowband system the symbol time is very long compared to the multipath delay spread on the channel. In effect, the multipath is combined into a single multiplicative distortion process (i.e., frequency nonselective fading). While this environment generates very little ISI and rarely requires sophisticated equalization techniques, the multipath distortion process can produce significant signal fading on mobile links and significant performance variations with antenna location on stationary links.

Achieving diversity in demodulation is the single most important aspect of data communication in a Rayleigh (non-line-of-sight) fading environment. Diversity is the reception of the information being transmitted via multiple independent (or nearly independent) channel realizations. The basic idea is simple, if the channel realizations are independent, the probability that all of them experience a deep fade simultaneously is

much less than the probability that any one of them is in a deep fade. The level of diversity, L_d, is an important design parameter in wireless data communications. Providing two levels of diversity in demodulation (L_d=2) can improve bit error probability (BEP) performance by 10-20dB over the L_d=1 case depending on the desired operating level [4].

Diversity is achieved by effecting a change in the phases of the multipath signals, producing a different interference pattern. Since the phase of each multipath signal is a function of the path length and the carrier frequency, the techniques most prevalent are frequency, time, location, and polarization diversity. For operation in the ITS spectrum allocations, only location and/or polarization diversity are practical. For example, frequency diversity requires transmission of multiple carriers having a sufficient spectral separation to produce different phases along the various paths. The 4 kHz bandwidth of the ITS channels is not wide enough for this. In summary, the best way to achieve diversity for wireless modems using the ITS spectral allocation is with multiple antennas either located at separate locations, or having different polarizations, or both. On a forward link (i.e., infrastructure to remote terminal), diversity is best achieved at the transmitter in order that the remote receiver can be small and inexpensive. The essential idea in transmitter diversity is to transmit signals (not necessarily of the same modulation) from multiple antennas which are either spatially separated or have a different polarization. A simple way to do this is to transmit the same signal from each

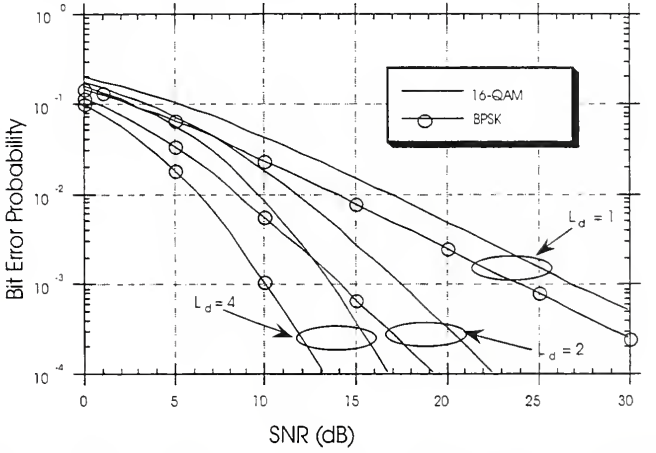


Figure 3: Effects of diversity on BEP performance for uncoded BPSK and 16-QAM.

antenna, but with a small frequency offset [5]. The technique will produce a time-varying fading at the receiver even in the absence of motion. It is a spectrally efficient scheme because the offset can be made small (< 40 Hz) and, in addition, the coding schemes and demodulation algorithms are essentially unchanged from a modem which does not use diversity. Lastly, with the frequency offset diversity method the interleaver

depth can be designed to obtain near ideal performance regardless of vehicle speed or Doppler spread.

Optimum demodulation of transmitter diversity waveforms requires coherent demodulation. Channel distortions (i.e., fading) can be estimated quite accurately by exploiting the bandlimited nature of fading by using pilot symbol assisted modulation (PSAM) [6, 7]. PSAM works by inserting known symbols into the data stream. The receiver uses the matched filter outputs corresponding to these known symbols to estimate the channel multiplicative distortion. The estimator is a simple linear filter (the minimum mean-squared error estimator for Rayleigh fading) and provides accurate estimates when the PSAM frame is designed appropriately. This type of channel estimation is an open loop structure which does not exhibit the acquisition anomalies that occur in traditional closed loop (e.g., phase-locked loop) structures. PSAM-based demodulation can provide performance within 1 – 2 dB of ideal coherent performance in time-varying fading with small frequency offsets [8]. If an accurate estimate of the frequency is available, then good performance can be provided even in the presence of a large frequency offset [9] without much additional complexity. The use of PSAM requires another level of synchronization in the receiver in order to locate the known pilot symbols.

The modem attains 3 levels of diversity by using 3 base station antennas and only a single antenna at the mobile receiver. For the forward link (base to mobile) the signal is transmitted from each antenna with a slight carrier frequency offset, thus inducing a deterministic fading process on the transmitted signal. The correlation function of this fading is dominated by the frequency offset induced variations so the interleaver depth can be set to allow nearly ideal interleaving to be achieved even when the mobile unit is stationary. The final step in achieving the full 3 levels of diversity is to insure that the forward error control (FEC) code has an effective Hamming distance of 3. For the reverse link (mobile to base), diversity would be attained simply through maximal ratio combining [4] of the inputs from the antennas.

5.1.2 High Rate QAM Codes

Divsalar and Simon [10] showed that the pairwise error event for trellis coded modulation (TCM) on Rayleigh fading channels with ideal interleaving is given by

$$P\{x \to \hat{x}\} \leq \left(\prod_{n \in \eta} \frac{\overline{E}_s}{4N_0} |x_n - \hat{x}_n|^2 \right)^{-1} \tag{1}$$

$$= (SNR)^{-d_H} \left(\prod_{n \in \eta} \frac{|x_n - \hat{x}_n|^2}{4} \right)^{-1} \tag{2}$$

$$= \left(\frac{1}{SNR} \right)^{m_1} \left(\prod_{m_2} \right) \tag{3}$$

where η is the set of all η for which $x_n \neq \hat{x}_n$, thus the cardinality of η is the Hamming distance, d_H. Metric $m_1 = d_H$ and metric m_2 is the product distance. If the BEP were graphed as a function of SNR, it would be seen from Eq. 3 that the Hamming distance determines the shape (i.e. steepness) of the curve, and the product distance is only a constant scaling, since it is not a function of SNR. Note that the Euclidean distance, the important design parameter in the additive white Gaussian noise (AWGN) case, is not as important in fading channels.

Given that an independent channel distortion is imposed on each symbol, it is possible to achieve L_D levels of diversity through the use of an error control code with Hamming distance L_D. The goal then in bandwidth efficient coding on fading channels is to find high rate codes with large Hamming distance, yet low computational complexity. The codes implemented in the ITS modem to date are listed in Table 1. The initially implemented codes [11] were simple repetition codes (with bit shuffling) to validate the idea of transmitter antenna diversity. The design of block codes is straightforward; however, as the constellation size increases the computational complexity of the demodulator becomes larger and a trellis structure offers some advantages for demodulation. The codes in [12] and [13] are IQ-TCM, where the in-phase and quadrature components of the signal are coded independently. This greatly reduces the complexity of the receiver compared to conventional TCM for a given Hamming distance. Ongoing development will implement codes using bit interleaving [14] in the continuing quest for the best performance complexity tradeoff.

Table 1: Details of codes implemented to date in the ITS modem.

Code	Rate	BW Eff.	Diversity	Complexity per bit
Kuo [11]	1/3	4/3	3	12
Kuo [11]	1/3	2	3	32
Ho & Cavers [12]	1/2	2	3	8
Al-Semari & Fuja [13]	3/4	3	2	21.3

Unfortunately, when TCM is combined with transmitter antenna diversity, the effective diversity which is achieved might be less than the Hamming distance of the code, as illustrated in Fig. 4. After de-interleaving when $L_D = 3$, channel samples are essentially as shown in Fig. 4(a) - all blocks of three channel samples are mutually uncorrelated, but pairs of channel samples separated by $L_D + 1$, $2L_D + 1$, etc., are highly correlated. Fig. 4(b) shows a length 5 error event path with $d_H = 4$ which only has an effective diversity of 2. The first and 4th code symbols are subjected to the same fading sample, so together

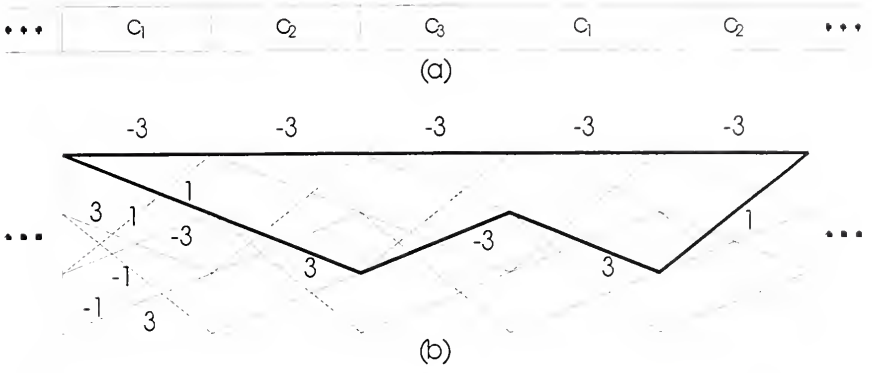


Figure 4. The Cavers rate 1/2 TCM doesn't achieve $L_D = 3$ when combined with transmitter frequency offset diversity.

they only contribute 1 level of diversity. The same phenomenon occurs with the second and fifth code symbols on a different channel fading sample. Future work will address how to design TCM codes that fully utilize the transmitter diversity structure.

5.2 Testing

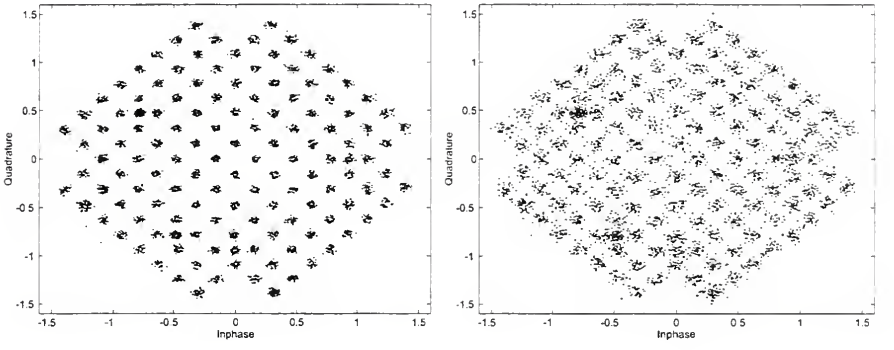
5.2.1 Field Testing of the Point-to-Point Modem

The current implementation of the experimental system uses a combination of hardware and software. The baseband modulator is implemented on a Motorola 56002 DSP. Samples are generated at a rate of 100 kHz. Using 28 samples per symbol period gives a symbol rate of 3571.4 Hz, the maximum that will fit in the FCC spectral mask. The baseband signal is sent to the Digital Up-Conversion (DUC) board which modulates the signal to an intermediate frequency (IF) of 21.4 MHz. Commercial off-the-shelf components are used the bring the signal up to a transmission frequency of 220.5825 MHz and to amplify it to 1/2 Watt. At the receiver the signal is amplified and down-converted to an IF of 10.7 MHz by an Analog Devices AD607 evaluation board. The IF signal is sampled at 40 MHz by the Harris HI5702 ADC and brought down to baseband by a Harris HSP50016 Digital Down-Converter (DDC). The DDC also decimates the sampling rate to 50 kHz. This sampled baseband signal is stored in the memory of a PC and then saved to a data file.

The remaining portion of the receiver and demodulator are implemented on the block-oriented software package, Signal Processing Worksystem (SPW). Although the final implementation uses a DSP for the demodulation, SPW was used for its versatility during the design phase.

Using the 4kHz channel bandwidth, the 3571.4 Hz symbol rate, and the synchronization sequence overhead, the bandwidth efficiencies can be calculated as 3.29 and 4.93 bps/Hz for the V.32 and V.33 modulation schemes, respectively. Field tests were conducted to observe the performance of this modem. Data was transmitted from the top of a parking garage in West Lafayette, IN near the Purdue University campus. The receiver was then used to collect the signal at a variety of locations throughout West Lafayette and Lafayette. Results generally fell into one of two categories. When the receiver did not have a direct line of sight with the transmitter, the resulting signal was not strong enough to demodulate (failure can be attributed to the digital phase locked loop (DPLL). Although the DPLL performs in a reasonable fashion once lock has been achieved, its performance during acquisition is rather poor without high SNR.

When the receiver had a direct line of sight to the transmitter, performance was substantially better. Received signal constellations for the V.33 modem are shown in Fig. 5 for transmission distances of 1.75 and 2.5 miles. In all V.33 cases, the BER was roughly 10^{-4} to 10^{-5} while V.32 transmissions gave no errors.



(a) (b)

Figure 5. Received signal constellations from field testing. (a) Receiver located approximately 1.75 miles from transmitter. (b) Receiver located approximately 2.5 miles from transmitter.

5.2.2 Field Testing of the Mobile Modem

The prototype wireless modem has evolved to the point where large amounts of data can be transmitted and analyzed. Using 0.5 watt transmit power from each of the three antennas, a working range of several miles is attained. Fig. 6 is a map of a typical field test in Lafayette, Indiana.

Three half wavelength vertically polarized antennas were used at the base station, and a single vertical whip antenna was used at the mobile unit. The base station antennas were mounted atop a six story parking garage and spaced about twenty feet apart in a linear array. For these tests, the symbol rate was 3.57 kbps, the pilot insertion rate was 10, the interleaver depth was 36, and the intentional frequency offset was 29.76 Hz.

Plots of a few of the PSAM channel estimates of 10 second bursts of data are shown in Fig. 7. The first plot is without transmitter antenna diversity to show just the fading induced by the multipath reception. The second plot also shows the intentional fading induced by the transmitter diversity scheme; it is obvious that the fading is more rapid and our design goal of using a shorter interleaver can be achieved.

The BEP of several of the locations in this field test is displayed in Fig. 8. Unfortunately, the automatic gain control (AGC) which we used to determine the SNR is only calibrated to within approximately +/- 5 dB, so there is some uncertainty in this figure. The data was taken at various vehicle speeds, ranging from 0 to 40 mph, over a wide variety of interference scenarios. This plot clearly shows a performance gain from the transmitter diversity scheme over standard interleaving and coding.

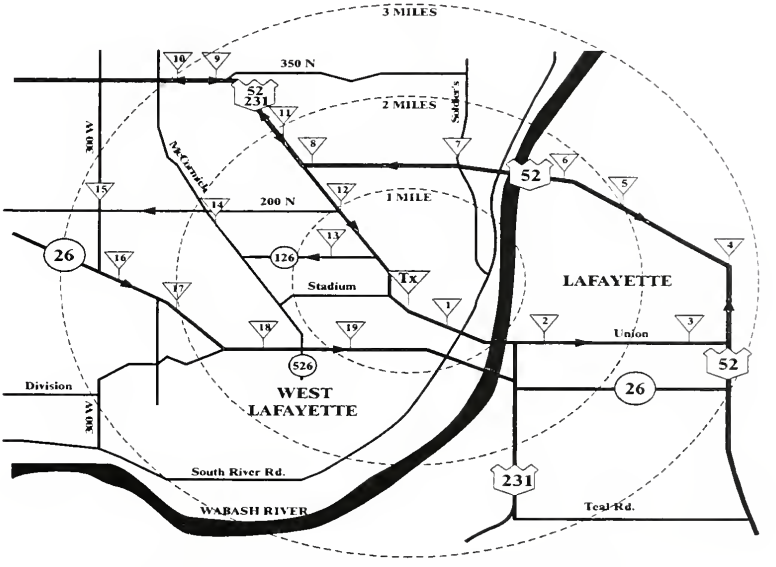


Figure 6. Field testing in the Lafayette area.

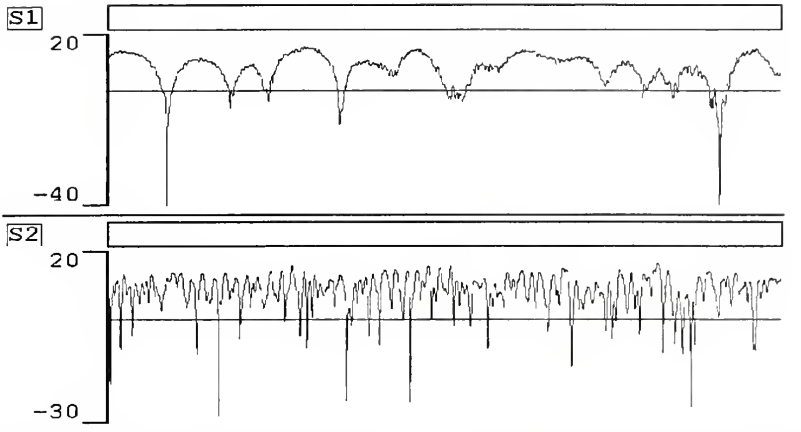


Figure 7. Sampled mobile channels (log scale). The first channel is with a single transmitter antenna and the second is with three transmitter antennas and frequency offset modulation.

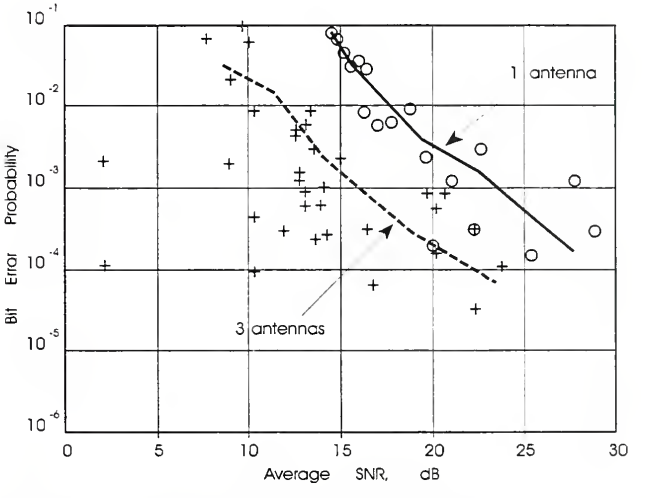


Figure 8. Field testing data for Ho & Cavers rate 1/2 TCM. The o's are 64,000 bit samples of 1 antenna data, the +'s are 64,000 bit samples of 3 antenna data, and the bold (solid and dashed) lines are averages.

5.3 Multiple Access and Networking Results

Many ITS applications of wireless communications fit into the following network scenario. Multiple terminals are located in the vicinity of a base-station. A two-way data communications capability must be provided so that the base can send control and configuration information to the terminals and the terminals can send their data to the base. Since the network capacity is limited by a narrowband channel, the network must be designed such that the transmission overhead is minimized. In the applications we envision, the terminals are heterogeneous in function and in the type and quantity of data they produce. The main issue is to design protocols with low overhead because in the sensor concentration application, individual messages are very short (just a few tens of bytes to indicate a vehicle detection and the speed of the vehicle). At the same time, however, attention must be paid to the vagaries of the wireless transmission medium.

One of the main distinguishing difference between wireless and wired networks arises because wireless communications is fundamentally a broadcast medium. Therefore, a transmitted message can in principal be received by a large number of other users (this implies obvious interference and security issues). Also, since the connection is not wired, it cannot always be guaranteed that there is a transmission path from every sender to every receiver. The most important parameters in the wireless network design are power and bandwidth efficiency.

There are two fundamental types of topologies for wireless networks.

1. **Hub-and-Spoke Networks**. Here a particular station serves as a hub of the network and all user stations are "located" at the ends of spokes around the hub. The hub thus controls all the user stations and monitors their communications. All communications (even between two users at the end of the spokes) must go through the hub, i.e., there is no provision for direct peer-to-peer communications. Examples of this network topology include cellular telephony and WLAN star topologies (such as the Windata and ALTAIR products).

2. **Peer-to-Peer Networks.** Here the name pretty much indicates the type of network topology (terminals in the network are allowed to communicate directly without the intervention and control of a hub). There are variations of this topology including the fully-connected network (any terminal has the functional capability to communicate with any other terminal) and multi-hop networks where full connection is not available (due to power or distance limitations) and terminals must cooperate to send messages.

For the sensor concentration application of this project it has been decided that the hub-and-spoke network topology is most suitable. It's advantages relative to peer-to-peer networks are: 1) the use of simple terminals is greatly facilitated because the hub can carry out control functions, 2) it allows for efficient use of transmitted power (hence good for battery operated mobiles), and 3) a centralized control function located in the hub can serve for power control (to mitigate interference) and reference timing. The hub-and-

spoke topology has disadvantages as well. It has reasonably large "store and forward" delay (which is not a large issue in the sensor concentration application) and the hub is a critical point for network reliability (the application is not, however, critical from a public safety point of view).

6. Conclusions

This report has provided a detailed overview of the design of a multimode communications architecture based upon the 220 MHz ITS spectral allocations. The results presented herein are a part of a larger project (funded in part by ITS-IDEA, Texas Instruments, and the National Science Foundation) that seeks to explore the limits of bandwidth efficiency in cellular stationary, mobile, and multiple access communications. The technical goals of spectral efficiencies of 3 bps/Hz for mobile operation and 5 bps/Hz for point-to-point operation have been met in field tests of the experimental SPW based modem. Effort continues to improve these spectral efficiencies further. In cooperation with the Electro-Sciences Laboratory at Ohio State University, transmitter and receiver hardware have been fabricated for deployment in a camera control function on the Borman Expressway.

7. Recommendations

The 220 MHz can serve INDOT as a general purpose link for low to medium rate data communications in a wide variety of applications. The most significant issue outstanding with regard to widespread implementation of the technology is the mass production cost and the availability of a reliable source of production versions of the device. Efforts are continuing at both Purdue and Ohio State toward further simplifications aimed at complexity reduction in the receiver. Regarding costs relative to other INDOT data communications alternatives and compatibility with existing equipment, the following tasks should be undertaken.

1. A detailed cost/benefit analysis should be made comparing the 220 MHz technology to the following alternative communications technologies: (1) wireline connections through the public switched telephone network, (2) wireless connections using a cellular service provider, and (3) spread spectrum radios in the industrial-scientific-medical (ISM) bands. Where applicable the cost comparison should consider transportation related applications for medium bit rate data communications.

3. A preliminary design study of interoperability issues should be performed for the 220 MHz technology in transportation applications. In particular, the design requirements for 170/270 traffic signal controller backplane compatibility must be worked out.

8. Implementation Suggestions

This project has leveraged work funded by ITS-IDEA, Texas Instruments, and the National Science Foundation to produce a wireless communications resource for data

communications on the Borman and other INDOT projects. The research has lead to a modem design optimized for multimode operation (stationary, mobile, and multiple access) with high bandwidth efficiency. None of the existing products geared towards ITS applications have these multiple access capabilities nor can they provide high spectral efficiency.

The communications architecture could be implemented to provide for multiple access communications in a local area network configuration as would be found in a sensor concentration application on the Borman Expressway. See Figure 9 for an illustration showing the sensor concentration scenario where traffic sensors are geographically distributed in a local area. Sensors in a cluster must be able to send their data to a local processor for preprocessing and concentration. Different types of sensors have different data communication requirements and sensors communicate asynchronously.

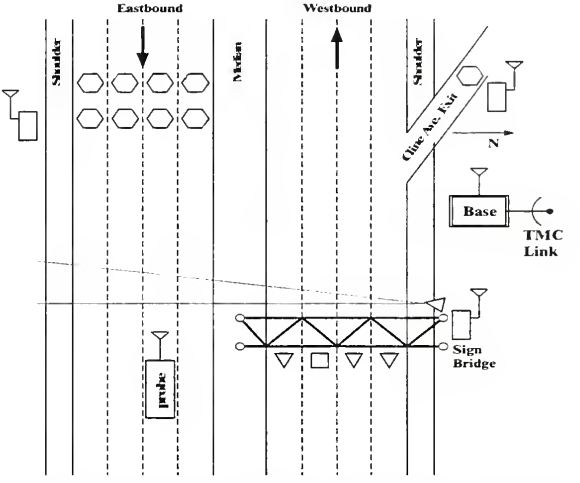


Figure 9. The sensor concentration scenario as might be implemented in a future Cline Avenue on the Borman Expressway.

Hardware and software for a version of the modem design presented here has been developed in cooperation with the Electro-Sciences Laboratory of the Ohio State University and Welkin Systems of San Diego, CA for deployment in a camera control application on the Borman Expressway. See Figures 10 and 11 showing the modem hardware and the associated camera controller.

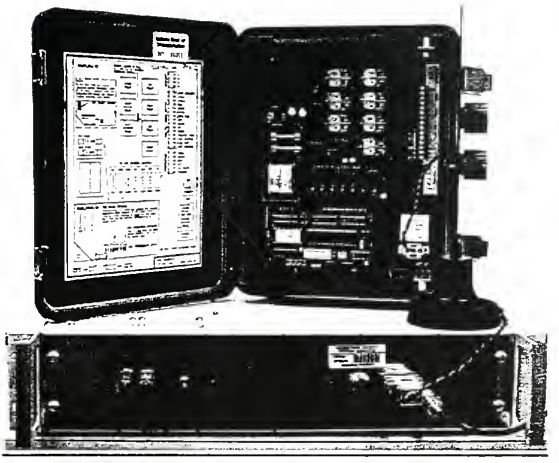


Figure 10. Borman point-to-point modem receiver hardware built by Welkin Systems. Shown on top of the receiver box is the camera control pan/tilt/zoom receiver.

Figure 11. Borman point-to-point modem transmitter hardware built by the Electro-Sciences Laboratory of the Ohio State University. Shown on top of the transmitter box is the camera control operator's touch pad and joystick.

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List of Tables

Table 1: Details of codes implemented to date in the ITS modem.

List of Figures

Figure 1: Basic Communications Architecture of the Phase I Borman Expressway ATMS.

Figure 2: Wide Area Communications Controller and Various Interfaces.

Figure 3: Effects of diversity on BEP performance for uncoded BPSK and 16-QAM.

Figure 4: The Cavers rate 1/2 TCM doesn't achieve $L_D = 3$ when combined with transmitter frequency offset diversity.

Figure 5: Received signal constellations from field testing. (a) Receiver located approimxately 1.75 miles from transmitter. (b) Receiver located approximately .5 miles from transmitter.

Figure 6: Field testing in the Lafayette area.

Figure 7: Sampled mobile channels (log scale). The first channel is with a single transmitter antenna and the second is with three transmitter antennas and frequency offset modulation.

Figure 8: Field testing data for Ho & Cavers rate 1/2 TCM. The o's are 64,000 bitsamples of 1 antenna data, the +'s are 64,000 bit samples of 3 antenna data, and the bold (solid and dashed) lines are averages.

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